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# Theory and Application of a Two-Layer Hall Technique

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Electron Devices Division
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Theory and Application of a Two-Layer Hall Technique

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ABSTRACT

The electrical characterization of epitaxial layers of silicon on substrates of the opposite conductivity type presents serious problems if the *p-n* junction at the interface has significant leakage current such that it cannot be used to effectively electrically isolate the two regions. In order to meet the need for nondestructively characterizing such structures, a modification of the conventional Hall technique was developed in which the Hall measurements are made simultaneously on both the epitaxial layer and its substrate, the interface impedance is measured, and the interaction between the two regions is modeled and taken into account. This technique can be used not only to measure the resistivity and Hall coefficient of each layer separately, but also to verify those cases in which the perturbing effects of a high resistivity substrate are negligible, thus justifying conventional measurements on the epitaxial layer.

This technique was used to measure the parameters of an *n*-type indium-doped silicon epitaxial layer on a bulk-grown *p*-type indium-doped substrate. The results suggest that the major *n*-type dopant in this specimen has a density of about $1 \times 10^{17}$ cm$^{-3}$ and an apparent activation energy of about 45 meV. Similar data were obtained on a second epitaxial layer grown on a high resistivity undoped substrate. These results argue strongly for the presence of one or more undesired sources of shallow donor contamination in the epitaxial growth system used to produce these specimens.

*Key Words:* Epitaxial growth; Hall measurements; indium-doped silicon; *p-n* junction isolation; two-layer structures.

## 1. INTRODUCTION

There are two well-established techniques for making Hall measurements on two-layer structures. If the two layers are of the same conductivity type, Hall measurements made before and after the removal of one of the

layers will provide the information necessary to characterize both layers [1]. If the two layers have opposite conductivity types, the *p-n* junction at the interface can often be used to electrically isolate the two regions and allow Hall measurements to be made on each layer separately. Frequently, the *p-n* junction at the interface has a large leakage current and the desired degree of isolation cannot be obtained. To handle this high leakage current case, a new technique was developed in which the interaction between the layers is modeled and equations are developed for obtaining the properties of each layer separately. In the special case of infinite interface impedance, this technique reduces to the case of complete isolation. In the other extreme of zero interface impedance, this technique reduces to the case of the intimate contact of the two layers of the same conductivity type. Therefore, the present technique bridges the gap between these two extremes and thus permits Hall measurements to be made on samples with arbitrary interface impedance.

The epitaxial silicon specimens that motivated the development of this technique were grown from indium solution with no other dopants intentionally added to the system. One would expect the epitaxial layer to be saturated with indium and, as a result, to be *p*-type. However, the layers were *n*-type. Actually, this behavior is not without precedent since alloyed indium contacts have been observed to be rectifying to *p*-type silicon and "ohmic" to *n*-type silicon [2,3]. One possible explanation is that interstitial indium is present and acting as a donor in the recrystallized regions of these contacts [4]. Another possibility is that some contamination, or other unidentified source of donor impurity, is present that overcompensates the indium acceptors that are incorporated into the regrown contact region. The search for the cause of this *n*-type behavior generated an interest in making Hall measurements on the epitaxial material. The high leakage current at the epitaxial layer-substrate *p-n* junction interface made it impossible to use conventional Hall techniques and necessitated the development of the two-layer Hall technique.

This report briefly outlines the details of this new two-layer technique and discusses the results obtained when using it to determine the nature of the *n*-type dopants in these specimens of indium-doped silicon.

## 2. SUMMARY OF THE TWO-LAYER HALL TECHNIQUE

### A. Measurement of Resistivity

Figure 1 is a schematic diagram of a symmetrical van der Pauw specimen cut from a homogeneous slice of silicon and provided with low impedance "ohmic" contacts at the end of each arm. This configuration is ideally suited for measurements of resistivity and Hall coefficient [5,6]. Resistivity is measured by passing a known current through two adjacent arms and measuring the voltage developed across the remaining two arms. The resistivity is computed by substituting this voltage and current, along with the specimen thickness, d, into the following equation:

$$\rho = \left(\frac{V}{I}\right)\left(\frac{\pi d}{\ln 2}\right). \tag{1}$$

Figure 2 shows two symmetrical van der Pauw specimens of different resistivity arranged back-to-back but separated, each provided with its own current, and each with its corresponding voltage measured separately. If the two specimens of figure 2 were each homogeneous in geometry and resistivity, and had negligible (or the same) resistance at the current carrying contacts and $V_1 = V_2$, the voltage distribution over the back-to-back surfaces would be the same. In this case, the two specimens could be brought together to form a two-layer composite structure without any current crossing the interface. The currents $I_1$ and $I_2$ would be unchanged, the voltages $V_1$ and $V_2$ would be equal, and the resistivities of each layer would be given by the following expressions:

$$\rho_1 = \left(\frac{V_1}{I_1}\right)\left(\frac{\pi d_1}{\ln 2}\right) \tag{2}$$

and

$$\rho_2 = \left(\frac{V_2}{I_2}\right)\left(\frac{\pi d_2}{\ln 2}\right). \tag{3}$$

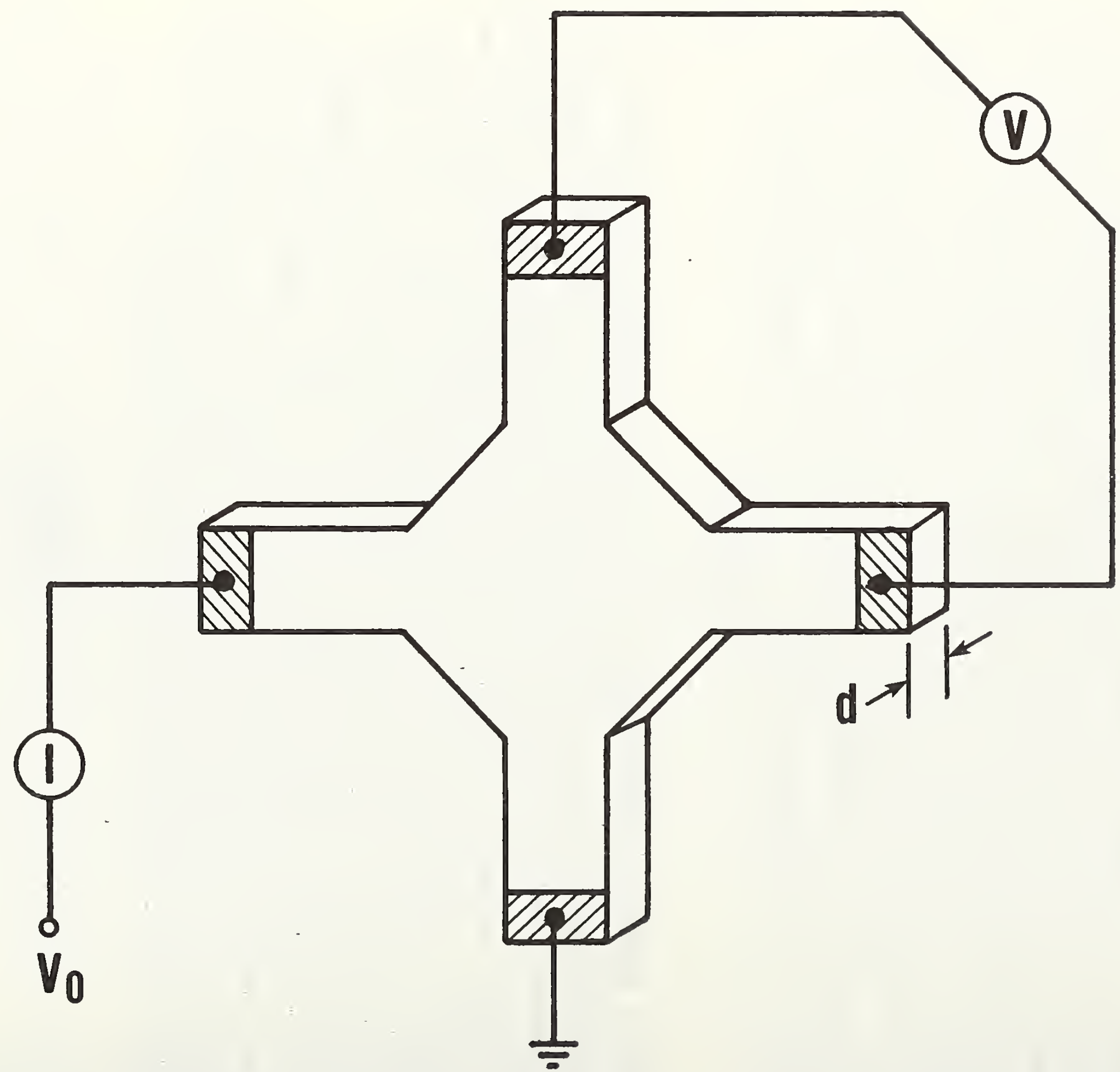



Figure 1. Conventional measurement of resistivity using the van der Pauw technique.

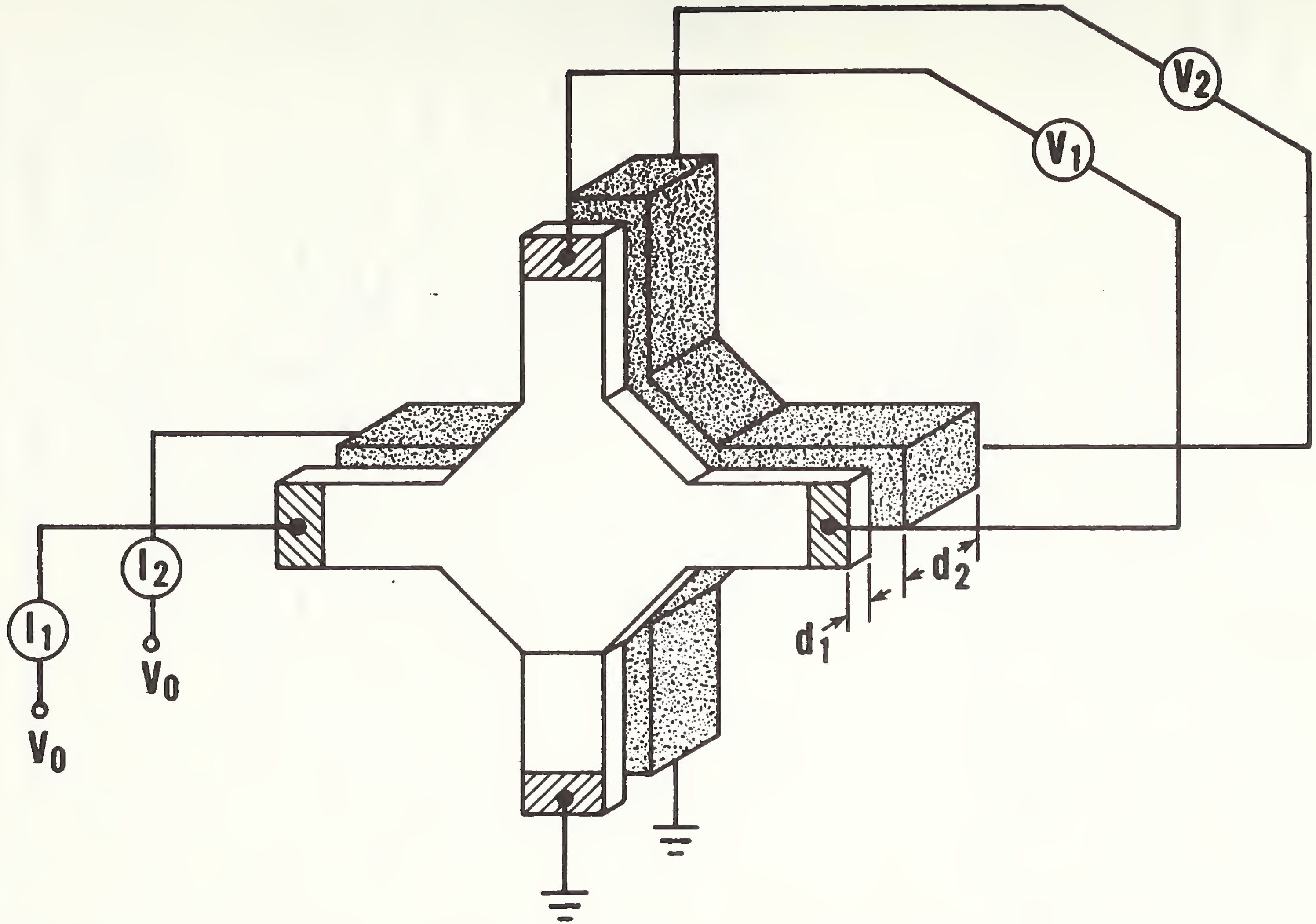



Figure 2. Simultaneous measurement of resistivity in two distinct van der Pauw specimens situated back-to-back with respect to each other.

Since the contact resistances may not be equal or negligible, external compensating resistors are placed in series with each of the four current leads as shown in figure 3. In addition, the current in each of the four arms is separately monitored. The resistors are adjusted to give zero voltage across the interface (i.e., $V_{DH} = V_{CG} = 0$) at the same time that $I_A = I_B$ and $I_E = I_F$. Violation of the assumption of uniformity of resistivity in either or both layers may show up at this point as the inability to achieve these conditions by varying $R_A$, $R_B$, $R_E$, and/or $R_F$. However, when these conditions can be achieved, or reasonably well approximated, a negligible amount of current crosses the interface and the resistivities of each layer are given by:

$$\rho_1 = \left(\frac{V_{DC}}{I_A}\right)\left(\frac{\pi d_1}{\ln 2}\right) \tag{4}$$

and

$$\rho_2 = \left(\frac{V_{HG}}{I_E}\right)\left(\frac{\pi d_2}{\ln 2}\right). \tag{5}$$

B. Measurement of Hall Coefficient

The van der Pauw specimen of figure 3 can also be used to measure the Hall coefficient of each layer. For this measurement, the current is passed through a pair of opposite contacts on each layer as shown in figure 4, instead of adjacent contacts as shown in figure 3. This change in current configuration does not alter the argument presented above leading to the conclusion that settings can be found for the resistances in series with each carrying arm that will cause the voltage distributions in the two layers to be the same and result in zero voltage across the interface (i.e., $V_{DH} = V_{BF} = 0$) at the same time that $I_A = I_C$ and $I_E = I_G$.

If a magnetic field is now applied perpendicularly to the plane of the interface between the two layers, Hall fields will be developed in the vertical direction of figure 4. If the two layers have different resistivities or different conductivity types, the Hall voltages developed within each layer will be different, thus upsetting the pre-

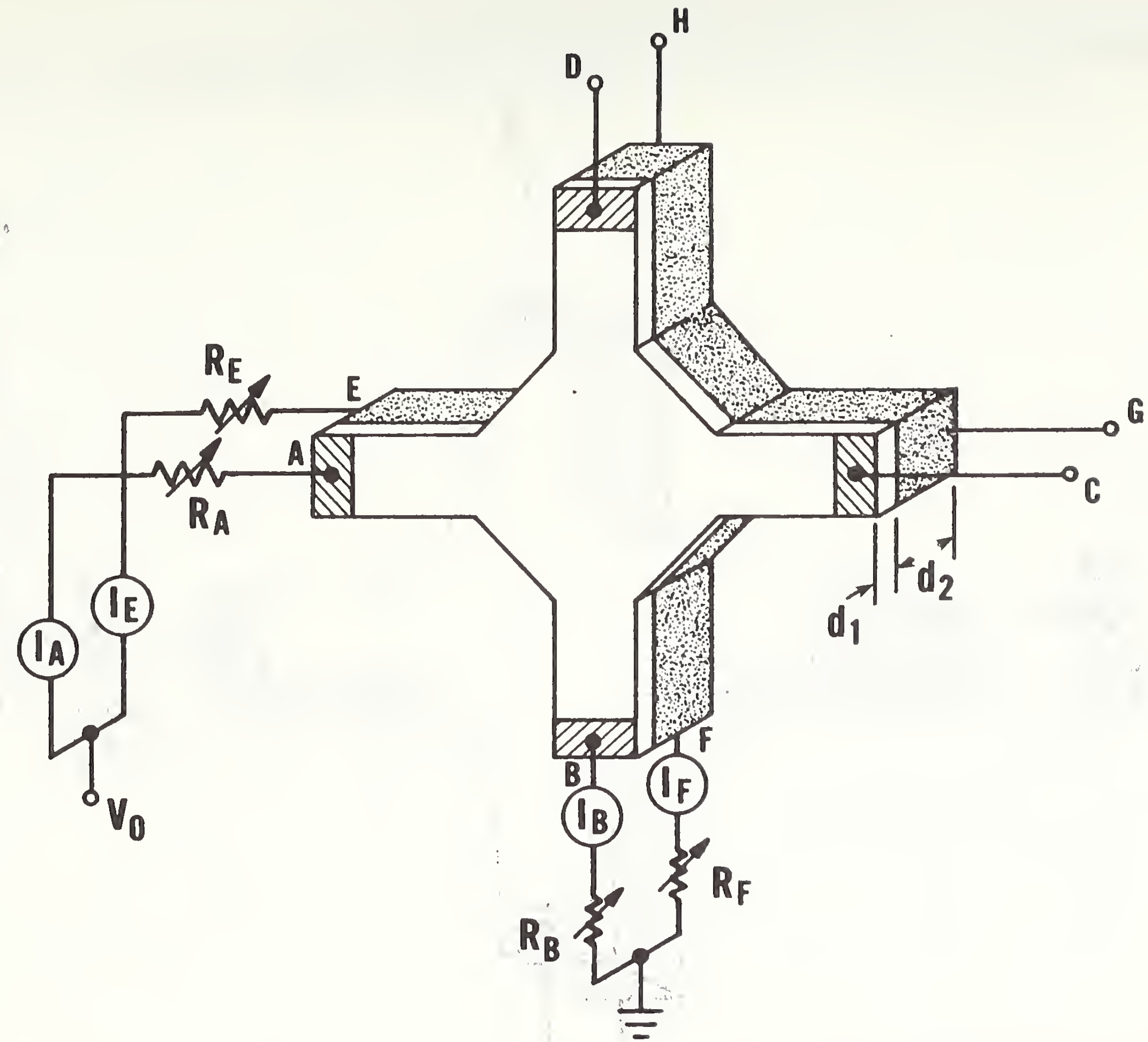



Figure 3. Simultaneous measurement of resistivity when the two specimens of figure 2 are brought into contact with each other to form a two-layer structure.

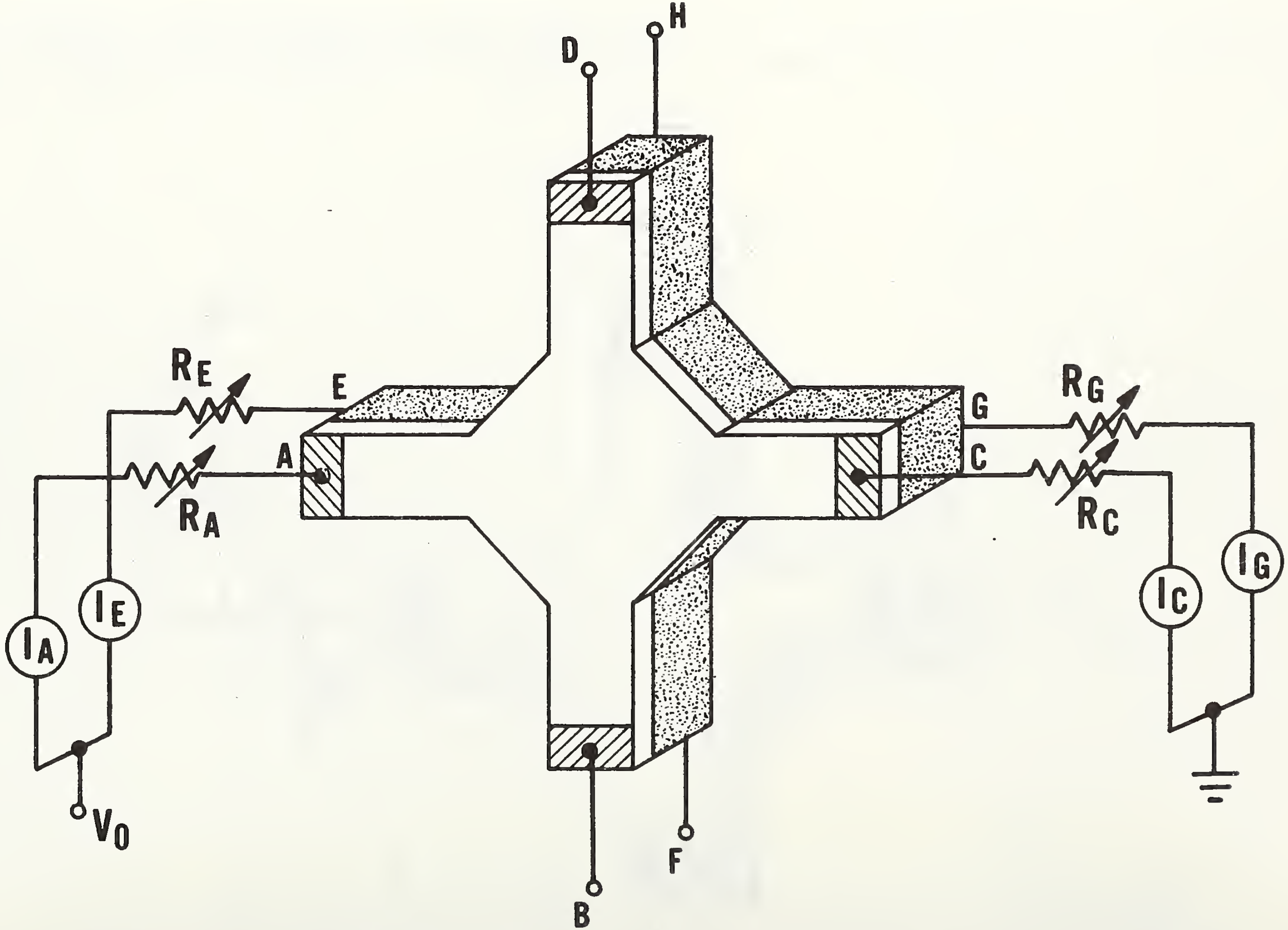


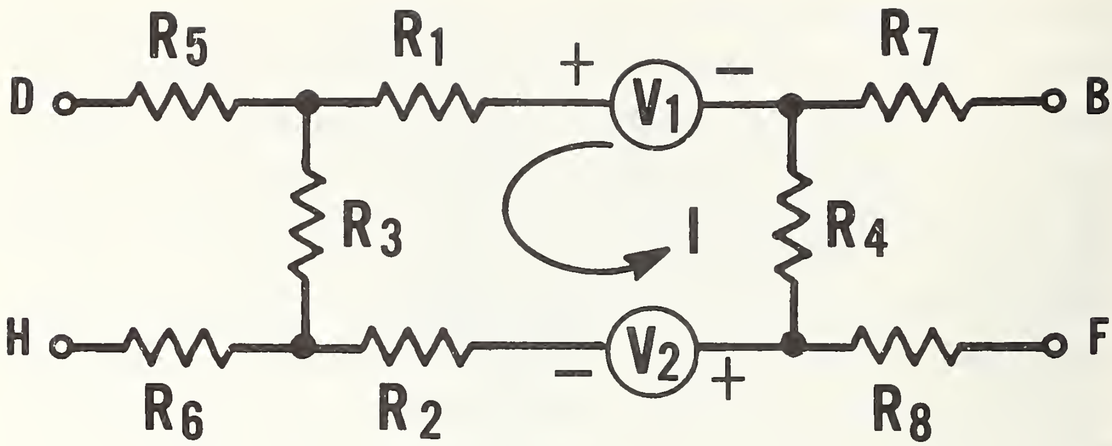

Figure 4. Simultaneous measurement of Hall coefficient in two-layer structures.

viously established equality of voltage distribution of the two layers. This will result in a difference in potential across the interface impedance, and currents will cross the interface between the two layers. Figure 5A is a schematic diagram of an equivalent circuit for this situation. The internally developed Hall voltages to be determined are designated $V_1$ and $V_2$. For layers of opposite conductivity type, $V_1$ and $V_2$ have the relative polarities indicated. The series resistances of the active region of each layer (i.e., the Thévenin equivalent resistances of the Hall voltage sources) are represented by $R_1$ and $R_2$. The series resistances of each layer in the arms of the van der Pauw structure correspond to $R_5$ through $R_8$. The resistors $R_3$ and $R_4$ represent the interface impedance coupling the two layers together.

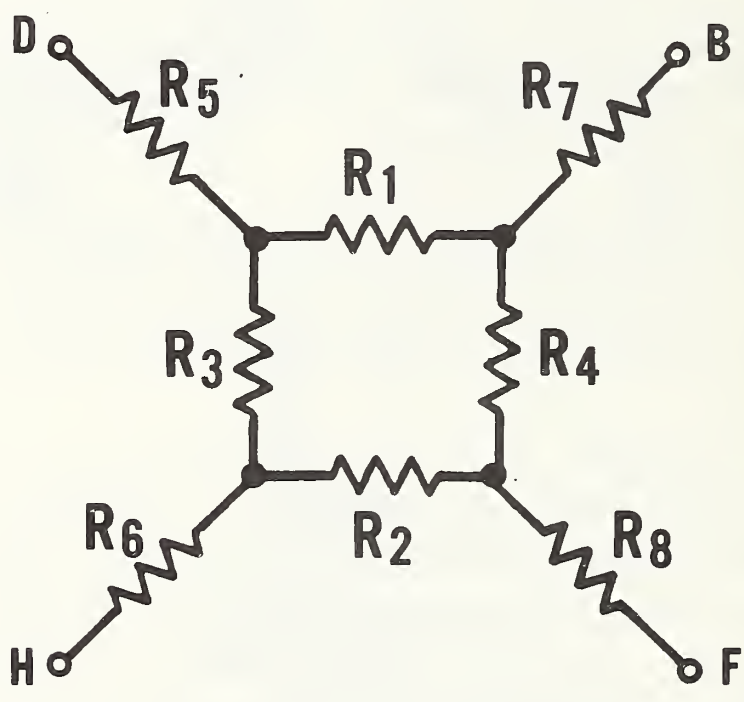
High values of $R_3$ and $R_4$ (compared to the larger of $R_1$ or $R_2$) correspond to the case of good isolation by a nonleaky *p-n* junction at the interface. In this case, the loop current I in figure 5A is small, and the internally developed Hall voltages $V_1$ and $V_2$ can be directly measured at the arm contacts D-B and H-F with a high impedance voltmeter (to avoid potential drops in $R_5$ through $R_8$).

Low values of $R_3$ and $R_4$ correspond to the case of intimate contact of two layers of different resistivity, but the same conductivity type. In this case, the resulting loop current will produce potential drops across $R_1$ and $R_2$ which prevent the direct measurement of $V_1$ and $V_2$ at the arm contacts.

Between these two extremes, there is an intermediate case of a leaky *p-n* junction at the interface that corresponds to intermediate values of $R_3$ and $R_4$. The interface *p-n* junction can be modeled in terms of linear resistors if the voltage across the junction is less than kT/q ($\approx$25 mV at room temperature). The circuit in figure 5A is not the most general equivalent circuit one could imagine for this situation, but it is one that appears to contain elements representing all of the essential interactions of this problem and, as will be shown below, is simple enough to lead to a practical measurement technique. It remains to be shown that this circuit is capable of modeling the situation with sufficient accuracy to produce a meaningful result.




A) EQUIVALENT CIRCUIT IN PLANE OF HALL FIELD




B) EQUIVALENT CIRCUIT OF A) IN ZERO MAGNETIC FIELD

Figure 5. Equivalent circuits of the specimen of figure 4 in the plane of the Hall contacts D-B and H-F.

It will be assumed throughout this discussion that high impedance voltmeters are used to measure differences in potentials between the contacts on the arms of the van der Pauw structure, so that the potential drops in the series resistances $R_5$ through $R_8$ can be neglected. In this case, the equivalent circuit of figure 5A can be used to show that:

$$V_{DB} = \frac{V_1[R_2 + R_3 + R_4] - V_2[R_1]}{R_1 + R_2 + R_3 + R_4} \tag{6}$$

and

$$V_{FH} = \frac{V_2[R_1 + R_3 + R_4] - V_1[R_2]}{R_1 + R_2 + R_3 + R_4} . \tag{7}$$

A parameter U which is a measure of uniformity of the interface impedance can be defined by:

$$U \equiv \frac{R_3}{R_4} = \frac{V_{DH}}{V_{FB}} . \tag{8}$$

For a perfectly uniform *p-n* junction at the interface, U would be unity. Since $R_1$ and $R_2$ represent the series resistances within each layer separately, their ratio N is given by

$$N = \frac{R_1}{R_2} = \frac{\rho_1 d_2}{\rho_2 d_1} , \tag{9}$$

where $\rho_1$ and $\rho_2$ are the resistivities of the two layers as measured by the technique discussed above.

If the applied magnetic field is now removed from the specimen of figure 4, the internally developed Hall voltages $V_1$ and $V_2$ disappear and the equivalent circuit can be redrawn as shown in figure 5B. If magnetoresistance effects can be neglected, the resistance values in figure 5B are equal to the corresponding resistance values in figure 5A. Two transfer impedances, $R_x$ and $R_y$, can be defined and measured as follows:

$$R_x = \frac{R_3 R_4}{R_1 + R_2 + R_3 + R_4} = \frac{V_{BF}}{I_{DH}} \tag{10}$$

and

$$R_y = \frac{R_1 R_2}{R_1 + R_2 + R_3 + R_4} = \frac{V_{DB}}{I_{HF}} . \qquad (11)$$

Equations (8) through (11) can be solved simultaneously for $R_1$, $R_2$, $R_3$, and $R_4$ in terms of the measured quantities U, N, $R_x$, and $R_y$. The results are substituted into eqs (6) and (7) which can then be solved simultaneously for $V_1$ and $V_2$:

$$V_1 = \frac{V_{DB}\left\{\left[\frac{UNR_y}{R_x}\right]^{1/2} + U + 1\right\} + V_{FH}\left[\frac{UNR_y}{R_x}\right]^{1/2}}{\text{DENOM}} \qquad (12)$$

and

$$V_2 = \frac{V_{FH}\left\{\left[\frac{UR_y}{NR_x}\right]^{1/2} + U + 1\right\} + V_{DB}\left[\frac{UR_y}{NR_x}\right]^{1/2}}{\text{DENOM}} \qquad (13)$$

where:

$$\text{DENOM} = \frac{\left\{\left[\frac{UNR_y}{R_x}\right]^{1/2} + U + 1\right\}\left\{\left[\frac{UR_y}{NR_x}\right]^{1/2} + U + 1\right\} - \frac{UR_y}{R_x}}{\left[\frac{UNR_y}{R_x}\right]^{1/2} + \left[\frac{UR_y}{NR_x}\right]^{1/2} + U + 1} . \qquad (14)$$

The Hall coefficient of each layer is then computed for these values of $V_1$ and $V_2$ in the conventional way [5,6]:

$$RH_1 = \frac{V_1 d_1}{I_1 B}$$

and

$$RH_2 = \frac{V_2 d_2}{I_2 B}$$

where all quantities in the equations are in SI units.

Two examples of the use of this technique to characterize a thin *n*-type epitaxial silicon layer on top of a thicker *p*-type bulk-grown substrate are presented in the following section. These specimens were prepared

by Dr. Barbara E. Sumner at the Night Vision and Electro-optics Laboratory, Ft. Belvoir, Virginia.

## 3. ILLUSTRATIONS OF THE USE OF THE TWO-LAYER TECHNIQUE

### A. For Making Measurements on Structures with Poor Interface *p-n* Junctions

The material that motivated the development of the above two-layer technique consisted of a 1.0-mil (0.025-mm) thick layer of *n*-type epitaxial silicon grown by liquid phase epitaxial techniques on top of a 14-mil (0.36-mm) thick substrate of bulk-grown *p*-type indium-doped silicon. The *n*-type conductivity of the epitaxial layer, which was initially demonstrated by thermal probe techniques, was completely unexpected because the layer was grown from indium solution, but otherwise not intentionally doped. Since these growth conditions would be expected to produce a layer saturated with indium, the question immediately arose regarding the nature and cause of the observed *n*-type conductivity. In an experiment designed to answer this question, a van der Pauw specimen was ultrasonically cut from this material, and metallic contacts were evaporated on each side of the four arms. Aluminum was used to contact the *p*-type substrate and gold-antimony was used to contact the *n*-type epitaxial layer. The current-voltage characteristic of this structure was linear between any two aluminum or any two gold-antimony contacts. It exhibited a very leaky *p-n* junction characteristic between any aluminum and gold-antimony contact. These results, plus the initial thermal probe result, leave little doubt that the epitaxial layer is *n*-type and the substrate is *p*-type. It was found that some of the apparent leakage of the interface *p-n* junction was due to the exposed regions of this junction around the edges of the van der Pauw specimen. This component of leakage was reduced significantly by etching the edge of the specimen to remove the damage caused by the ultrasonic cutting. However, at room temperature, the leakage current was still too large to permit the *p-n* junction at the interface to be used to electrically isolate the two regions of this specimen. The room temperature results given in table 1 were obtained by the above two-layer modified Hall technique on this edge-etched van der Pauw specimen.

Table 1. Results on Specimen 10-SYS-1-In Obtained by Two-Layer Technique at Room Temperature.

| Layer | Parameter | Value |
|---|---|---|
| Epitaxial (*n*-type) | Resistivity | 0.085 Ω·cm |
| | Hall coefficient | -65 $cm^3/C$ |
| | Carrier density | $9.6 \times 10^{16}$ $cm^{-3}$ |
| | Hall mobility | 760 $cm^2/V{\cdot}s$ |
| Substrate (*p*-type) | Resistivity | 0.818 Ω·cm |
| | Hall coefficient | +172 $cm^3/C$ |
| | Carrier density | $2.6 \times 10^{16}$ $cm^{-3}$ |
| | Hall mobility | 210 $cm^2/V{\cdot}s$ |

Since the interface between the two layers was visible on the cut edges of the specimen, the thickness of each layer was measured optically with a microscope. Instrumental problems, specimen symmetry, and specimen inhomogeneity can often be determined by the change in resistivity or Hall coefficient with current reversal or contact rotation. The resistivity values quoted in table 1 represent the average of measurements made with current reversals and with 90-deg contact rotation. The small deviations of the individual measurements about this average (5 percent for the epitaxial layer and 6 percent for the substrate) indicate that this specimen was fairly homogeneous. In addition, the resistivity was observed to change less than 2 percent with a sevenfold increase in current and is thus considered to be independent of the magnitude of the measuring current used.

The Hall coefficient data in table 1 represent the average of values obtained with current reversals, magnetic field reversals, and 90-deg contact rotation. For contact rotation, the deviation of the two measurements from the average was 6 percent for the epitaxial layer and 1 percent for the substrate. This good agreement for the two configurations is another indication that the specimen was fairly homogeneous.

The carrier density was computed from the resistivity and Hall coefficient (assuming equal drift and Hall mobility). The measured value of Hall mobility for the electrons in the epitaxial layer is a very rea-

sonable one for silicon doped with approximately $10^{17}$ donors per cubic centimeter. Likewise, the mobility and carrier density in the substrate are very reasonable values for indium-doped silicon at room temperature.

The bulk-grown indium-doped *p*-type substrate of this specimen rapidly deionizes as the temperature is lowered below room temperature. Therefore, if the *n*-type epitaxial layer does not deionize too rapidly, a temperature can be reached where the resistivity of the substrate becomes so large relative to the epitaxial layer that its perturbing effects can be neglected. In this temperature regime, the epitaxial layer can be characterized by conventional Hall techniques without making any connection to, or correction for, the substrate.

Figure 6 shows the results of such Hall measurements in which the apparent density of electrons in the epitaxial layer is plotted as a function of 1000/T. In the vicinity of liquid nitrogen temperature ($1000/T \approx 13$) where substrate effects can be neglected, the measured points have been fitted by a theoretical curve generated by a computer solution of the charge balance equation [7]. The dopant parameters so obtained are listed in table 2. The value of acceptor density was estimated from the solubility of indium at the 900°C growth temperature of this layer.

Table 2. Dopant Parameters Deduced from an Analysis of the Data Presented in Figure 6.

| Dopant | Density $cm^{-3}$ | Activation Energy meV |
|---|---|---|
| Donor 1 | $9 \times 10^{16}$ | 45 |
| Donor 2 | $2 \times 10^{16}$ | 10 |
| Acceptor | $1.5 \times 10^{16}$ | ? |

The dominant donor state has an apparent activation energy of about 45 meV which is the activation energy of phosphorus in silicon. However, for a phosphorus density close to $10^{17}$ $cm^{-3}$ and the compensation ratio of 0.14 calculated from the densities in table 2, one would expect a decrease of the activation energy from its value at low phosphorus den-

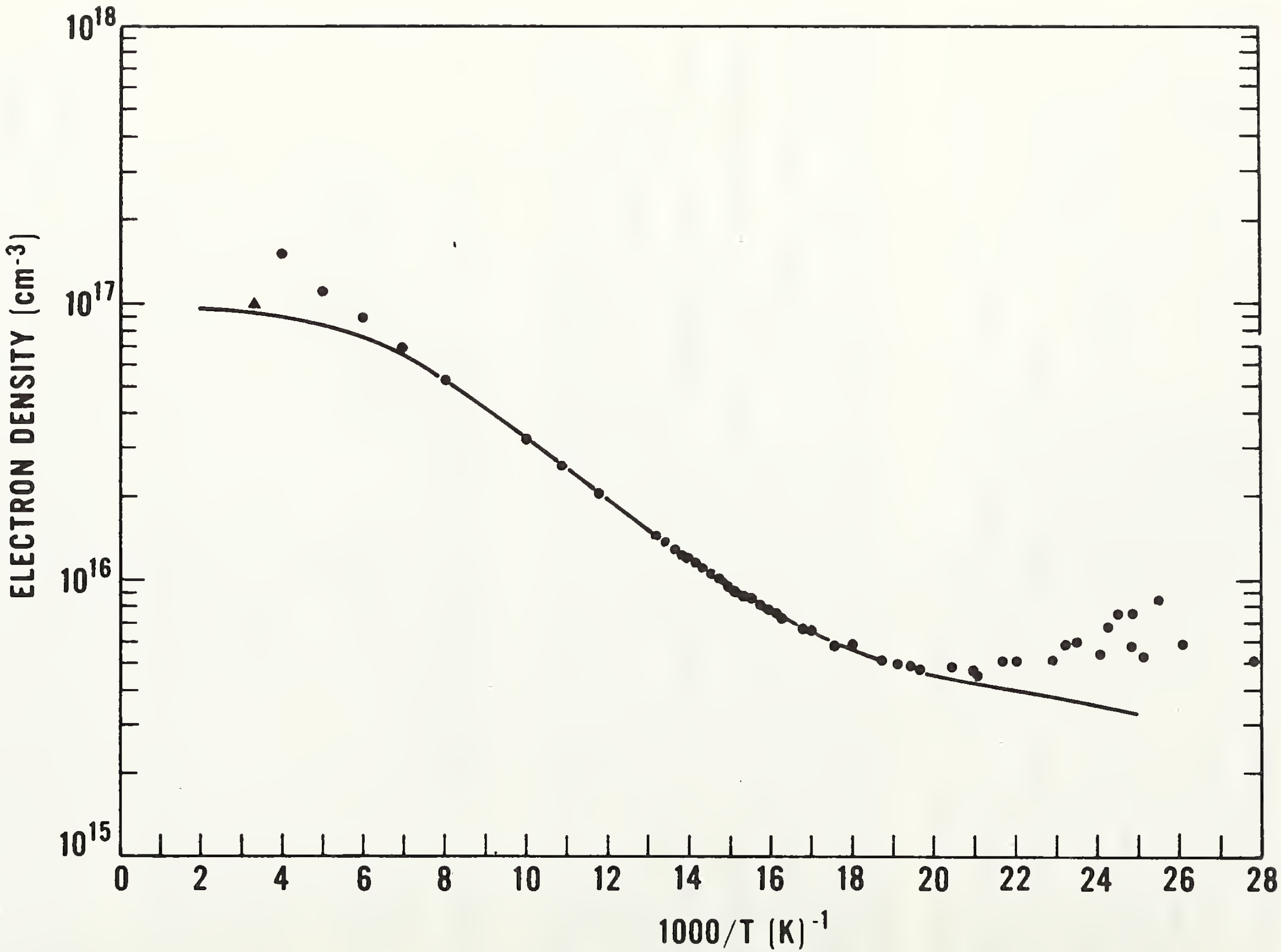



Figure 6. Electron density in the epitaxial layer of Specimen 10-SYS-1-In deduced from conventional Hall measurements performed at reduced temperature (circular points) fitted with a theoretical curve over the interval from 1000/T = 8 to 1000/T = 20. The triangular point represents the result of the two-layer technique at room temperature.

sities [8-11]. Neutron activation analysis measurements show that the dominant donor is not arsenic ($\Delta E$ = 49 meV) or antimony ($\Delta E$ = 39 meV). It was impossible with activation analysis to determine if phosphorus was present at the level expected because of the large amount of indium in the substrate (indium decays with the emission of a beta particle with about the same energy as the beta particle from phosphorus). Since even a few millielectronvolts change in the activation energy gives a noticeably poorer fit to the data in figure 6, one must assume either that the dominant donor in this specimen is not phosphorus or that the compensation is less than that of table 2. The latter possibility is consistent with the results of Penin [9] who showed that the decrease in activation energy is more pronounced in highly compensated material.

The tendency of the electron density curve to level off below liquid nitrogen temperature has been attributed to the presence of a second donor state with an activation energy less than that of the dominant donor state. The incorporation of this second donor state into the theoretical model upon which the curves of figure 6 are based has extended the range of agreement to 1000/T = 20. The tendency of the electron density curve to become completely level and then increase at still lower temperatures is not understood at this time. At these lower temperatures, the measured values are erratic and, to some extent, nonreproducible as evidenced in figure 6 by the spread of points beyond 1000/T = 20.

The failure of the theoretical curve to fit the measured points at the higher temperatures is understandable in view of the substrate effects that enter the picture as the temperature approaches room temperature. This is the region where the present two-layer technique is needed to make meaningful measurements. The theoretical curve extrapolates to a value that is in good agreement with the room temperature result which was obtained by the two-layer technique. This point is indicated by the triangular point in figure 6. This agreement supports the results of the room-temperature two-layer technique.

The following section deals with the same type of epitaxial layer on an undoped high resistivity substrate. In this case, the two-layer technique was used to demonstrate that the substrate effects were negligible and thus validate the conventional Hall measuring technique.

B. For Demonstrating that the Interaction Between the Two Layers is Negligible

This section discusses measurements on material which was also grown by liquid epitaxy except that the substrate was high resistivity *p*-type silicon rather than the indium-doped silicon used previously. As before, the epitaxial layer was *n*-type with a thickness of 1.0 mil (0.025 mm). A van der Pauw specimen was ultrasonically cut from the material and contacts were evaporated and alloyed on each side of the four arms. The exposed regions of the *p-n* junction were not etched. Measurements were made by the two-layer technique at room temperature and 77 K in the manner discussed previously. Measurements were also made at these same temperatures on both layers by the conventional technique in which no connections were made to the contacts on the layer not being measured. The results are summarized in tables 3 and 4. The values obtained for the epitaxial layer by the two techniques are in excellent agreement and support the conclusion that the interaction between the two layers is small enough that the epitaxial layer can be correctly measured by the conventional technique.* The conventional technique was then used to obtain the electron density as a function of temperature; these results are shown in figure 7. These data were fitted by a theoretical curve with a donor density of $1.7 \times 10^{17}$ cm$^{-3}$ and an activation energy of 45 meV. The measurements on this specimen do not extend to low enough temperatures to determine if a second donor and an acceptor level are present, but since the growth conditions for this specimen were similar to those for the first specimen, the parameters for donor two and the acceptor

*The converse is not true. Conventional measurements on the high resistivity substrate may be seriously perturbed by the lower resistivity epitaxial layer. Therefore, agreement between the two techniques is not expected for the substrate as indicated in table 3.

were included in the fit of this specimen. However, these levels have a negligible effect on the fit in the temperature range shown in figure 7. The 45-meV activation energy for the dominant donor state suggests that the unknown impurity may be phosphorus. However, as before, this conclusion is clouded by the fact that with significant compensation the activation energy of phosphorus should be somewhat lower than 45 meV.

Table 3. Results on Specimen 8-SYS-2-In at Room Temperature.

| Layer | Parameter | Conventional Technique | Two-Layer Technique |
|---|---|---|---|
| Epitaxial | Resistivity | 0.0605 Ω·cm | 0.0592 Ω·cm |
| | Hall coefficient | $-37.2$ cm$^3$/C | $-37.5$ cm$^3$/C |
| | Carrier density | $1.68 \times 10^{17}$ cm$^{-3}$ | $1.66 \times 10^{17}$ cm$^{-3}$ |
| | Hall mobility | 614 cm$^2$/V·s | 635 cm$^2$/V·s |
| Substrate | Resistivity | 530 Ω·cm | 69,000 Ω·cm |
| | Hall coefficient | $+4.82 \times 10^4$ cm$^3$/C | $-2.3 \times 10^7$ cm$^3$/C |
| | Carrier density | $1.3 \times 10^{14}$ cm$^{-3}$ | $2.7 \times 10^{11}$ cm$^{-3}$ |
| | Hall mobility | 90.6 cm$^2$/V·s | 335 cm$^2$/V·s |

Table 4. Results on Specimen 8-SYS-2-In at 77 K.

| Layer | Parameter | Conventional Technique | Two-Layer Technique |
|---|---|---|---|
| Epitaxial | Resistivity | 0.201 Ω·cm | 0.197 Ω·cm |
| | Hall coefficient | $-2.96 \times 10^2$ cm$^3$/C | $-2.95 \times 10^2$ cm$^3$/C |
| | Carrier density | $2.11 \times 10^{16}$ cm$^{-3}$ | $2.12 \times 10^{16}$ cm$^{-3}$ |
| | Hall mobility | 1472 cm$^2$/V·s | 1495 cm$^2$/V·s |
| Substrate | Resistivity | 78.7 Ω·cm | 80.5 Ω·cm |
| | Hall coefficient | $7.42 \times 10^5$ cm$^3$/C | $7.18 \times 10^5$ cm$^3$/C |
| | Carrier density | $8.41 \times 10^{12}$ cm$^{-3}$ | $8.69 \times 10^{12}$ cm$^{-3}$ |
| | Hall mobility | 9430 cm$^2$/V·s | 8920 cm$^2$/V·s |

## 4. CONCLUSIONS

A technique was developed for characterizing epitaxial layers on substrates of opposite conductivity type for situations where the *p-n* junction does not effectively isolate the two layers. This two-layer tech-

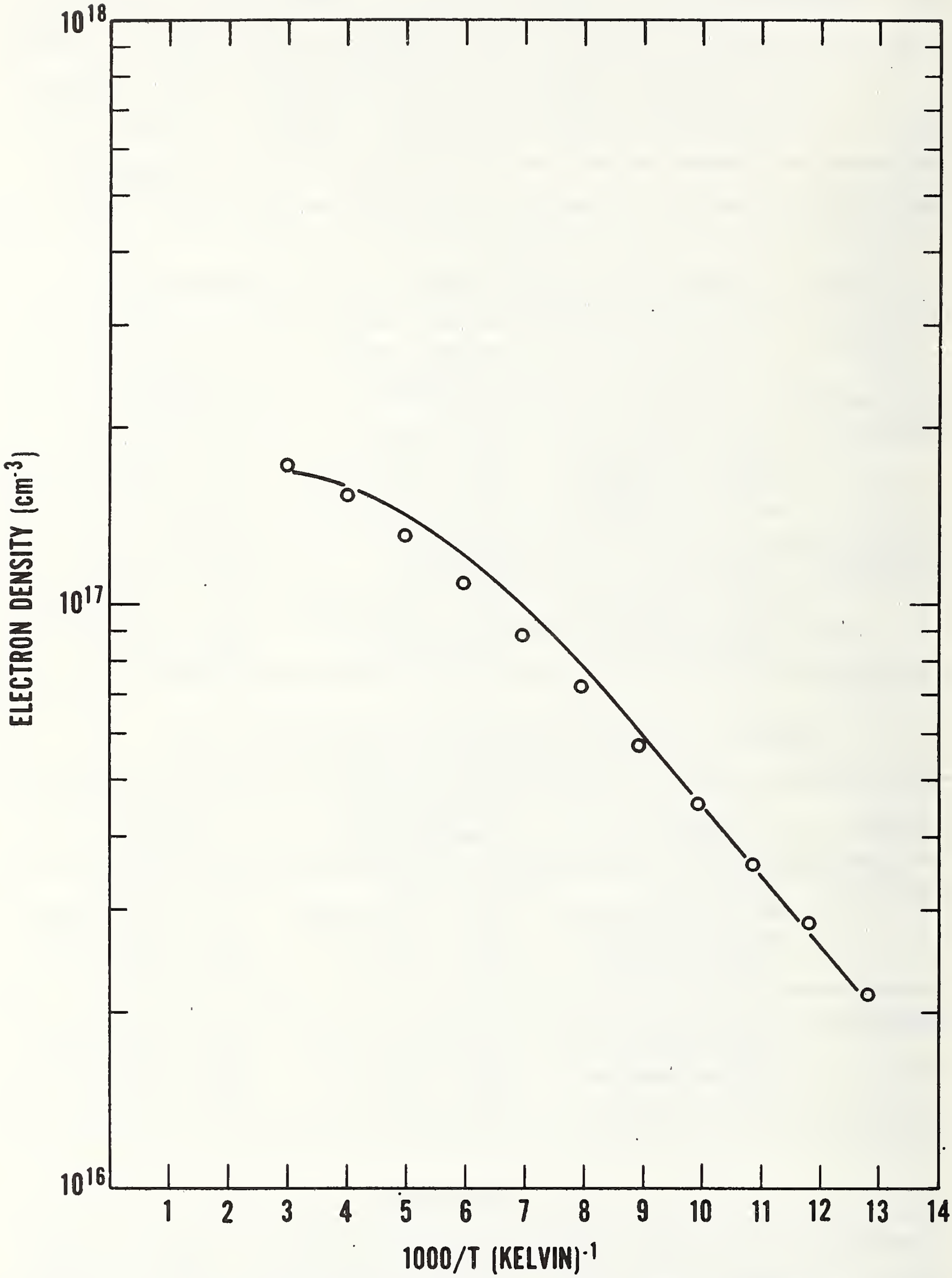



Figure 7. Electron density in the epitaxial layer of Specimen 8-SYS-2-In obtained by conventional Hall measurements (points) and a theoretical fit to the data.

nique was used to determine the room temperature resistivity and Hall coefficient in both layers of an epitaxial specimen, and the results agreed well with those obtained from a theoretical fit based on low temperature measurements by the conventional technique. For another specimen, the two-layer technique demonstrated that substrate effects were negligible, thus validating the conventional technique. In both epitaxial specimens, an unknown *n*-type impurity was identified with an apparent activation energy of 45 meV and a density of about $10^{17}$ $cm^{-3}$. The activation energy suggests that the impurity may be phosphorus. However, since the activation energy of phosphorus should be somewhat lower than 45 meV at a concentration of $10^{17}$ $cm^{-3}$ and with significant compensation, there is a possibility that this donor is some other species with a low-density activation energy somewhat above 45 meV. Arsenic ($\Delta E$ = 49 meV) has been ruled out by neutron activation analysis. Other possibilities that may satisfy these criteria are bismuth ($\Delta E$ = 0.069 eV) and interstitial indium ($\Delta E$ = ?). (Note added in proof: The presence of phosphorus at a density of about $10^{17}$ $cm^{-3}$ has been confirmed in Specimen 10-SYS-1-In by Dr. Te-Tse Chang of the National Bureau of Standards using electron paramagnetic resonance.)

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16. ABSTRACT (*A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.*)

The electrical characterization of epitaxial layers of silicon on substrates of the opposite conductivity type presents serious problems if the p-n junction at the interface has significant leakage current such that it cannot be used to effectively isolate the two regions. In order to meet the need for nondestructively characterizing such structures, a modification of the conventional Hall technique was developed in which the Hall measurements are made simultaneously on both the epitaxial layer and its substrate; the interface impedance is measured; and the interaction between the two regions is modeled and taken into account. This technique can be used not only to measure the unperturbed resistivity and Hall coefficient of each layer separately, but also to verify those cases in which the perturbing effects of a high resistivity substrate are negligible, thus justifying conventional measurements on the epitaxial layer.

This technique was used to measure the parameters of an n-type indium-doped silicon epitaxial layer on a bulk-grown p-type indium-doped substrate. The results suggest that the major n-type dopant in this specimen has a density of about $1 \times 10^{17}$ $cm^{-3}$ and an apparent activation energy of about 45 meV. Similar data were obtained on a second epitaxial layer grown on a high resistivity undoped substrate. These results argue strongly for the presence of one or more undesired sources of shallow donor contamination in the epitaxial growth system used to produce these specimens.

17. KEY WORDS (*six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons*)

Epitaxial growth; Hall measurements; indium-doped silicon; p-n junction isolation; two-layer structures.

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